Simultaneous Communications/Tracking/Navigation for Multiple Spacecraft (in a beam) in Deep Space

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Outline of Talk

Background and Challenges

- Notional Mars Regional Navigation Satellite System (MRNSS)

Simultaneous Communications/Tracking/Navigation

- Simultaneous Uplink, and 2-Way Doppler/Ranging
- Simultaneous Delta-DOR: Same Beam Interferometry (SBI)

Can Simultaneous Communications/Tracking Enable New Mission Concept and Science?

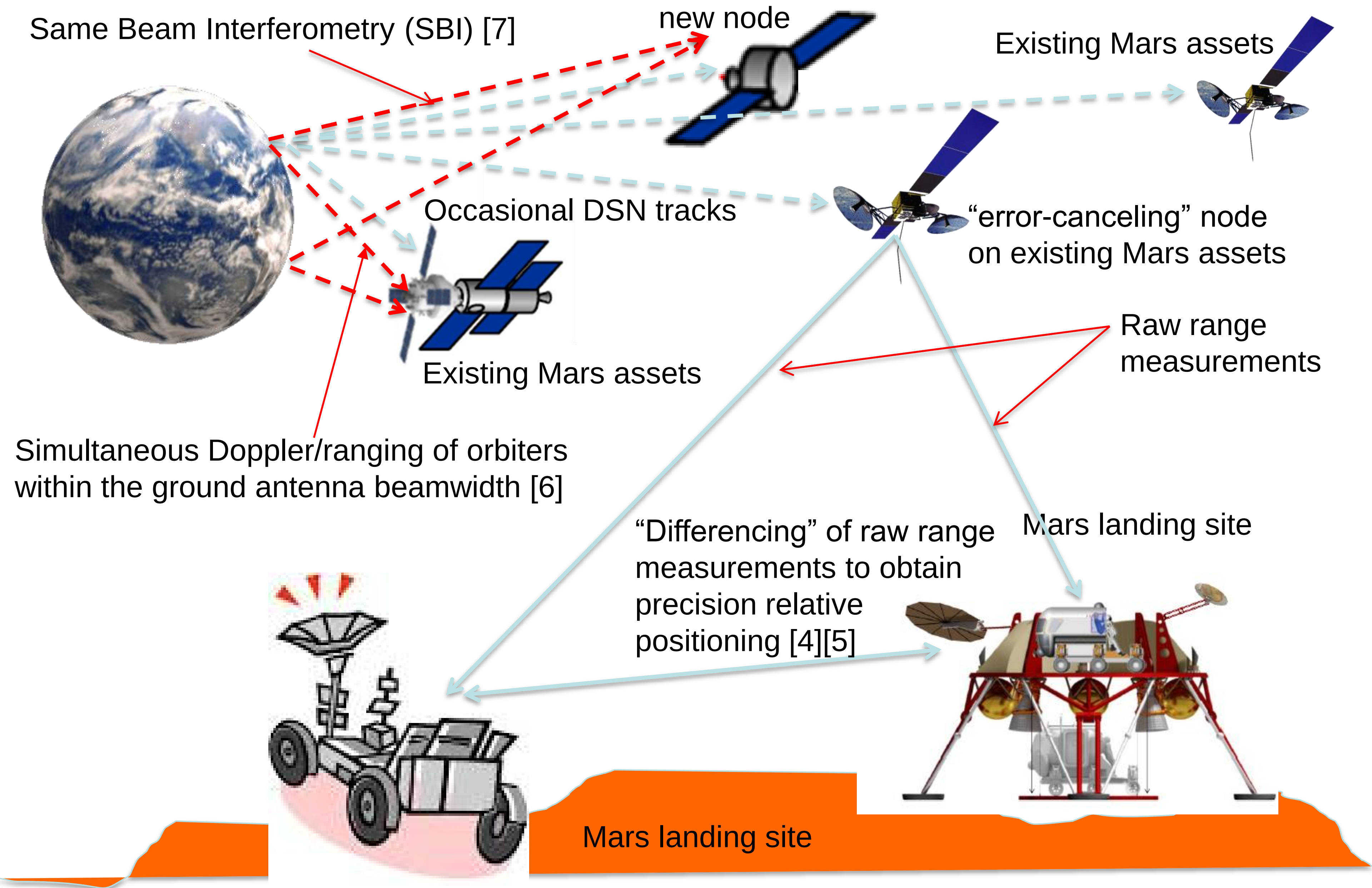
Background and Challenges (1)

- Typically one DSN ground station communicates with one spacecraft in deep space
- At Mars when multiple spacecraft are in the beam, one ground station can receive multiple downlinks (and one uplink) via MSPA, which is a static form of FDMA
- Traditional deep space tracking techniques include Doppler, ranging, and delta-DOR
- 2-Way Doppler/ranging requires tight coordination between ground and flight (Doppler compensation), and one ground station tracking one spacecraft (1-to-1)
- Delta-DOR is 1-way, but requires two ground station tracking one spacecraft (2-to-1)
- When number of missions increase, and for missions with multiple spacecraft, there might not be enough DSN antenna assets to meet missions' communications and tracking needs
- There is a desire to extend the current deep space communications and tracking techniques to support multiple spacecraft in a beam to improve the antenna usage efficiency

Background and Challenges (2)

- In 2016 we proposed a low-cost low-maintenance Mars Regional Navigation Satellite System (MRNSS) to support human Mars missions [8]:
  - Capitalize on the build-up of orbiting and surface infrastructures on Mars during the human Mars exploration era [1][2][3]
  - Leverage on a new geometric trilateration method that simultaneously performs absolute positioning and relative positioning [4][5]
  - Introduce the concept of using relative positioning that provides regional navigation services in the vicinity of a human Mars landing site (~100 km), thereby relieving the stringent requirements on orbit determination (OD) of Mars navigation satellites
  - Extend current DSN's tracking approaches of pairing one or two dedicated ground stations to one spacecraft for a period of time to simultaneously tracking of multiple Mars orbiters
    - Simultaneous Doppler/ranging [6]
    - Same Beam Interferometry [7]

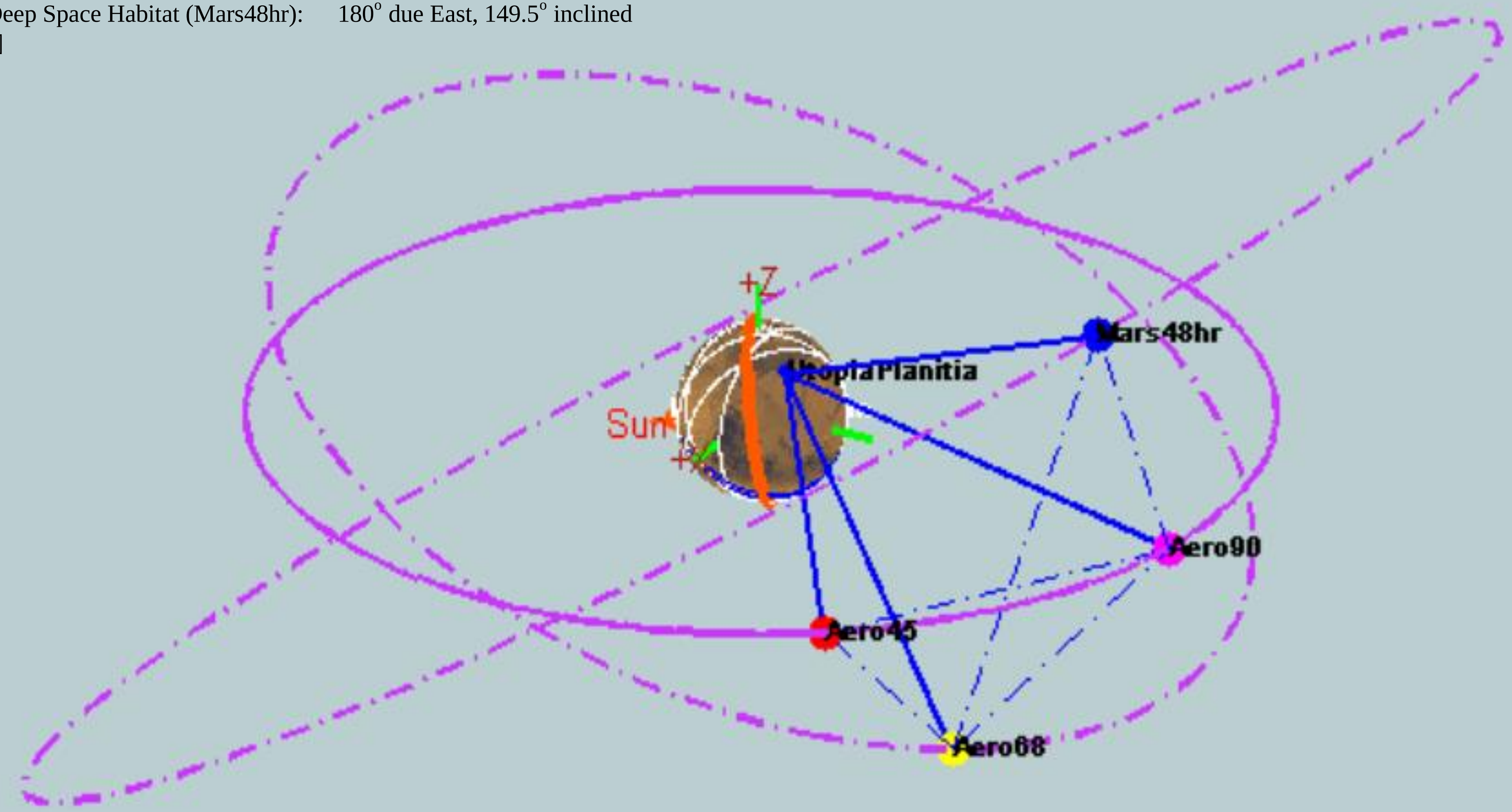
Mars Regional Navigation Satellite System (MRNSS) [8]



Mars Regional Navigation Satellite System (MRNSS) [8]

Orbits of the Notional Mars Navigation Nodes (3-D View)

Utopia Planitia:	182.5° due East, 46.7° due North
Aerostationary orbiter 1 (Areo45):	162.5° due East
Aerostationary orbiter 2 (Areo90):	207.5° due East
Aerosynchronous orbiter (Areo68):	180° due East and 20° inclined
Deep Space Habitat (Mars48hr):	180° due East, 149.5° inclined



Mars Regional Navigation Satellite System (MRNSS) Preliminary Results on Localization Accuracy

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.00	3273.85	6547.69	13095.39	32738.48	65476.99	196431.3	229169.9
	0.10 cm	11.27	3273.70	6547.54	13095.23	32738.32	65476.82	196431.1	229169.7
	0.25 cm	28.19	3273.56	6547.35	13095.01	32738.08	65476.58	196430.9	229169.5
	0.50 cm	56.37	3273.51	6547.12	13094.69	32737.71	65476.19	196430.5	229169.1
	1.00 cm	112.74	3274.15	6547.03	13094.24	32737.04	65475.45	196429.7	229168.3
	2.00 cm	225.48	3278.35	6548.30	13094.06	32735.98	65474.10	196428.1	229166.7
	5.00 cm	563.71	3313.95	6563.76	13099.34	32735.15	65471.23	196423.9	229162.4

Table 1. S_{3D} Absolute Localization Error standard deviation (cm) of the New Scheme. PDOP=113.17.

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	14.43	21.57	35.07	65.44	160.06	319.04	956.04	1115.33
	0.10 cm	21.59	26.82	38.47	67.27	160.75	319.32	956.05	1115.32
	0.25 cm	42.77	45.58	53.22	76.58	164.76	321.27	956.58	1115.75
	0.50 cm	81.89	83.33	87.69	103.45	178.67	328.48	958.82	1117.63
	1.00 cm	161.95	162.62	164.84	173.62	226.38	356.41	968.34	1125.72
	2.00 cm	323.00	323.28	324.34	328.78	359.12	452.05	1006.71	1158.71
	5.00 cm	806.95	806.99	807.34	808.99	821.36	865.36	1246.30	1371.59

Table 2. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 100 km. Sigma = 100 m. Delta = 100 m.

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.14	1.59	3.18	6.35	15.87	31.73	95.20	111.07
	0.10 cm	16.03	16.10	16.32	17.20	22.47	35.45	96.42	112.10
	0.25 cm	40.08	40.10	40.18	40.53	42.99	50.93	103.02	117.79
	0.50 cm	80.15	80.16	80.19	80.36	81.59	85.99	123.99	136.48
	1.00 cm	160.31	160.30	160.32	160.39	160.97	163.19	185.83	194.34
	2.00 cm	320.62	320.61	320.61	320.63	320.89	321.95	333.77	338.52
	5.00 cm	801.54	801.53	801.52	801.52	801.58	801.93	806.47	808.38

Table 3. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 10 km. Sigma = 100 m. Delta = 100 m.

200 – 400 folds improvement in RMSE accuracy

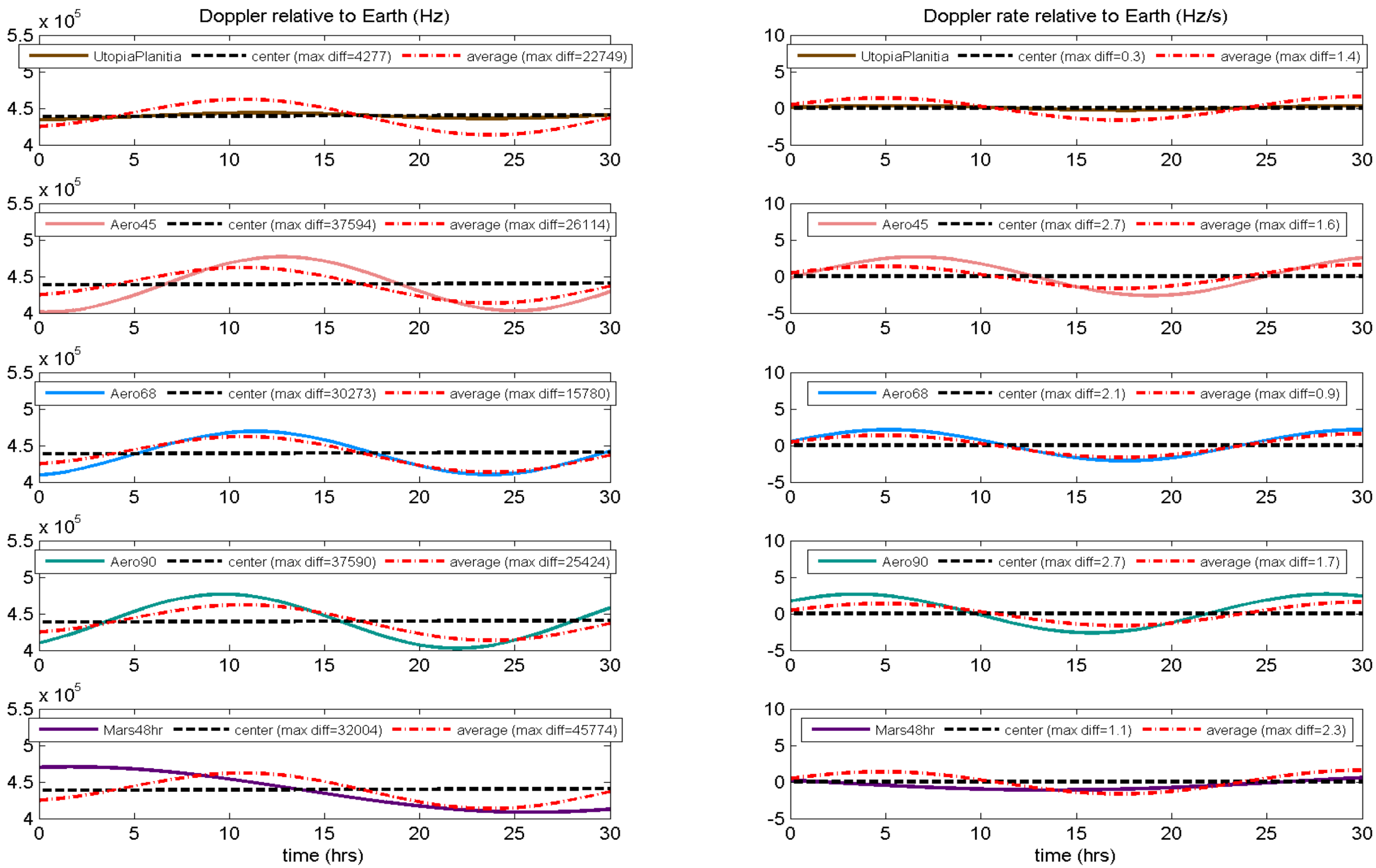
Sigma: media delay
Delta: clock bias

Simultaneous 2-Way Communications/Doppler/Ranging: System Approach

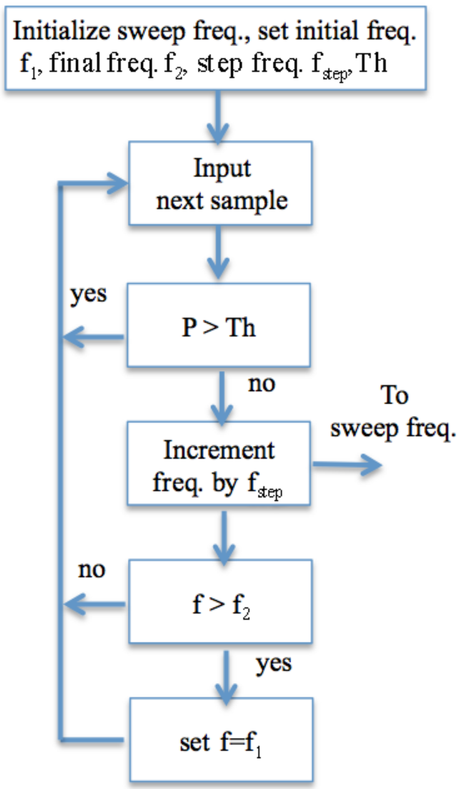
- Assume X-band, which supports low rate commands/telemetry
- The Mars orbiters all lie within the same beamwidth of a DSN 34-m BWG antenna
- For *N* orbiters, the downlinks operate in *N* allocated frequency bands separated by *N-1* guard bands to prevent interference
- Flight and ground upgrades:
  - The *N* orbiters time-share a single uplink; commands differentiated by SCID (MUPA) [9]
  - The ground "Doppler-compensates" the uplink carrier signal in either way:
    - With respective to the Mars center
    - With respective to the average (centroid) of Doppler's of *N* orbiters

    Guard bands must be wide enough to accommodate the residual Doppler. Preliminary simulations: residual Doppler and Doppler rate are bounded by 45 KHz & 2.6 Hz/s
  - Flight radio upgrades:
    - A different turn-around-ratio for each spacecraft so the same uplink would be coherently "turned-around" to modulate the telemetry and ranging signals on a different allocated downlink frequency
    - A well-designed tracking loop that can sweep, acquire, and track the unknown uplink carrier phase and high residual Doppler frequency
  - Ground station uses existing MSPA for telemetry/Doppler/range processing

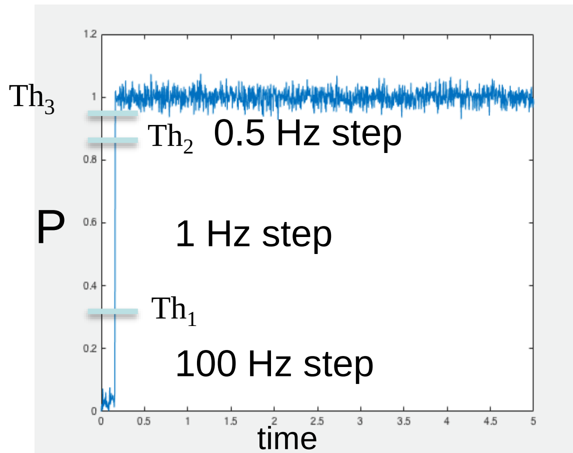
Simultaneous 2-Way Communications/Doppler/Ranging
Doppler and Doppler Rate Profiles

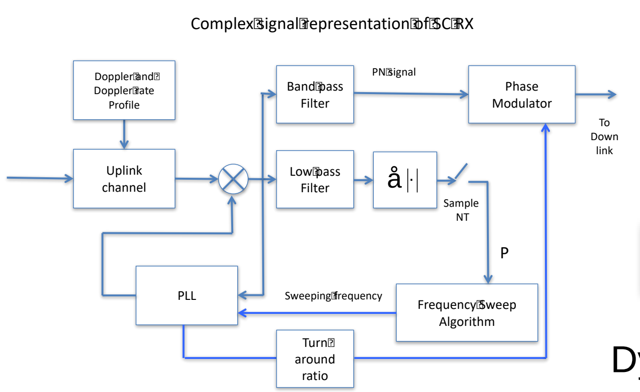


Simultaneous 2-Way Communications/Doppler/Ranging: Smart PLL Tracking

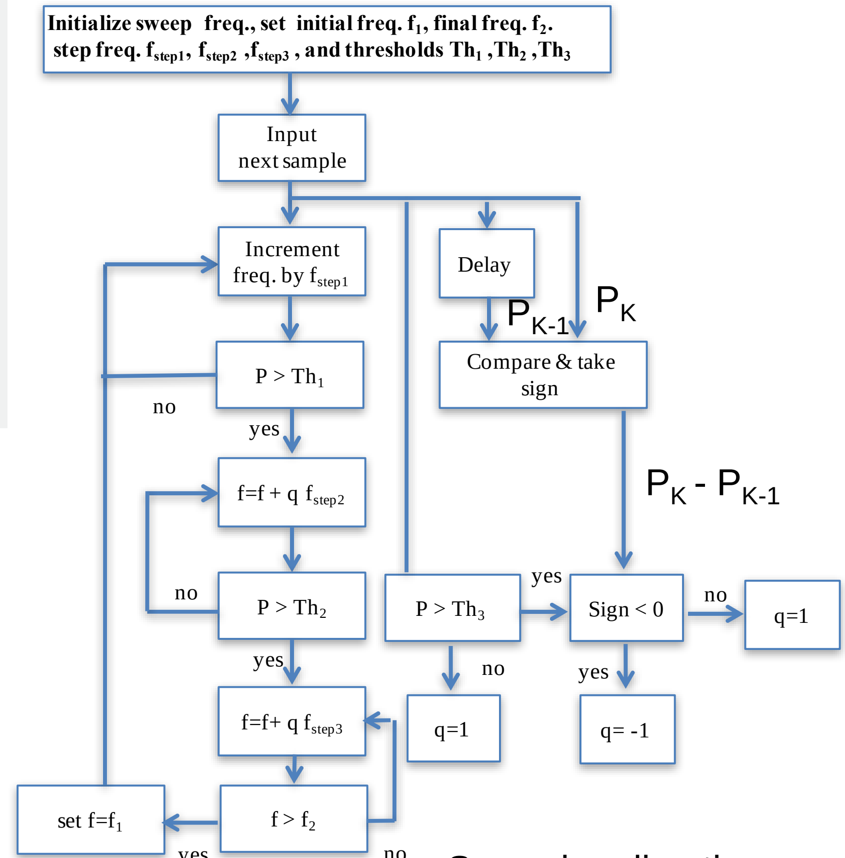


Current straight-forward Electra sweeping algorithm





A new frequency sweep acquisition algorithm

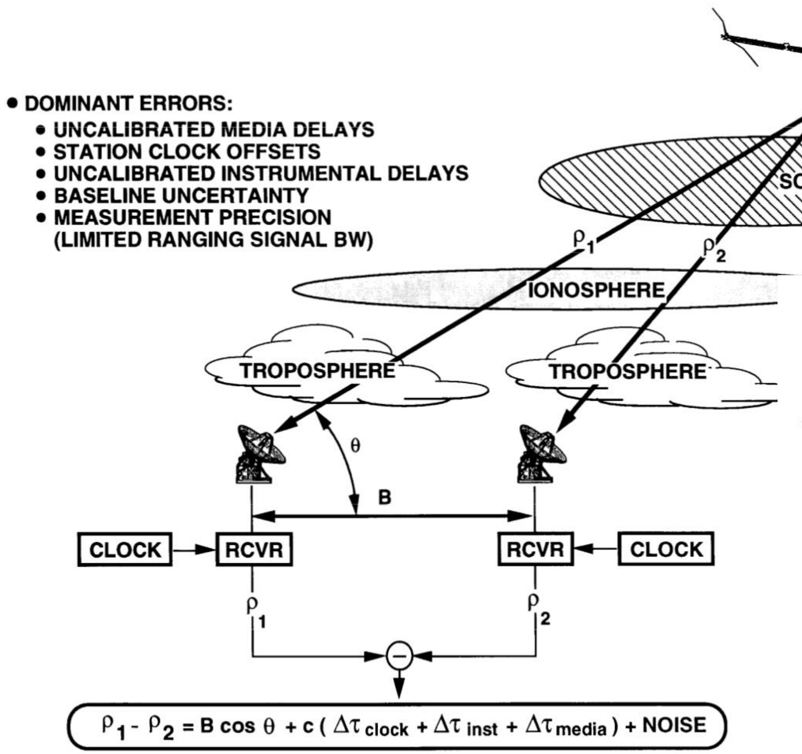


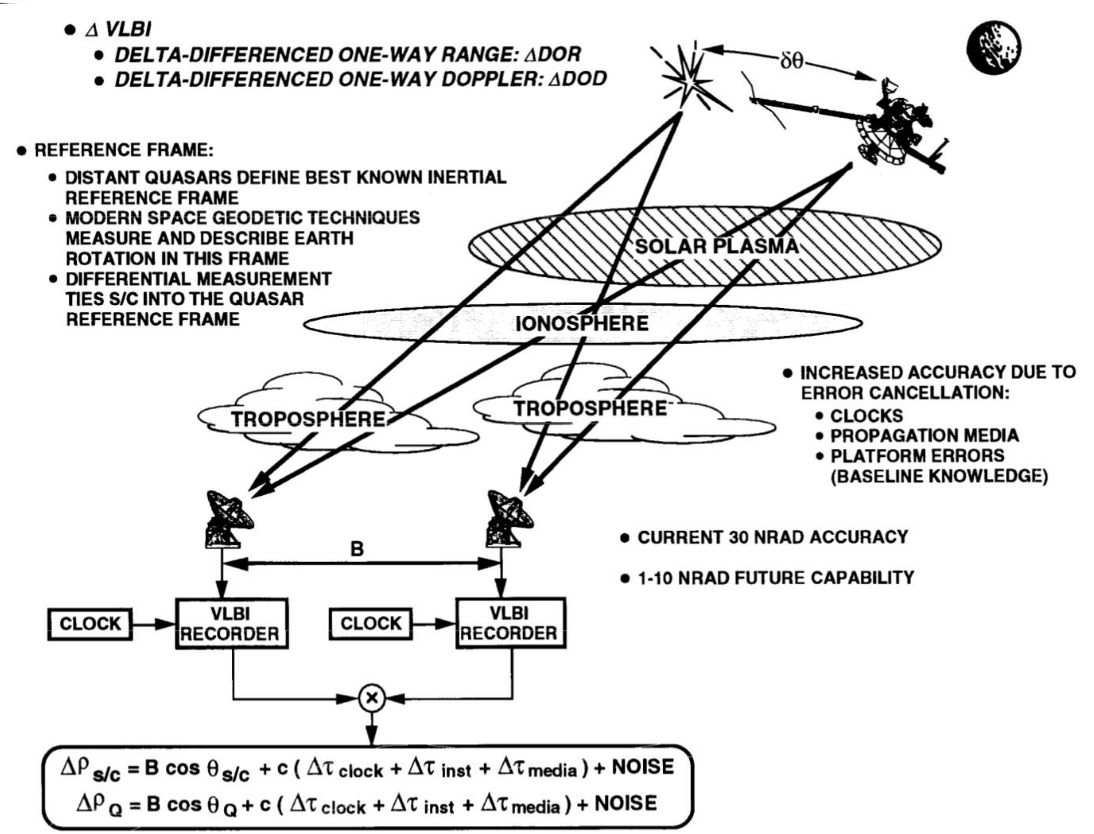
Dynamic sweeping circuit

Sweeping direction estimation circuit

Simultaneous Delta-DOR: Theory of Delta-DOR

Diagrams from "The Evolution of Deep Space Navigation: 1962-1989," by Lincoln Wood

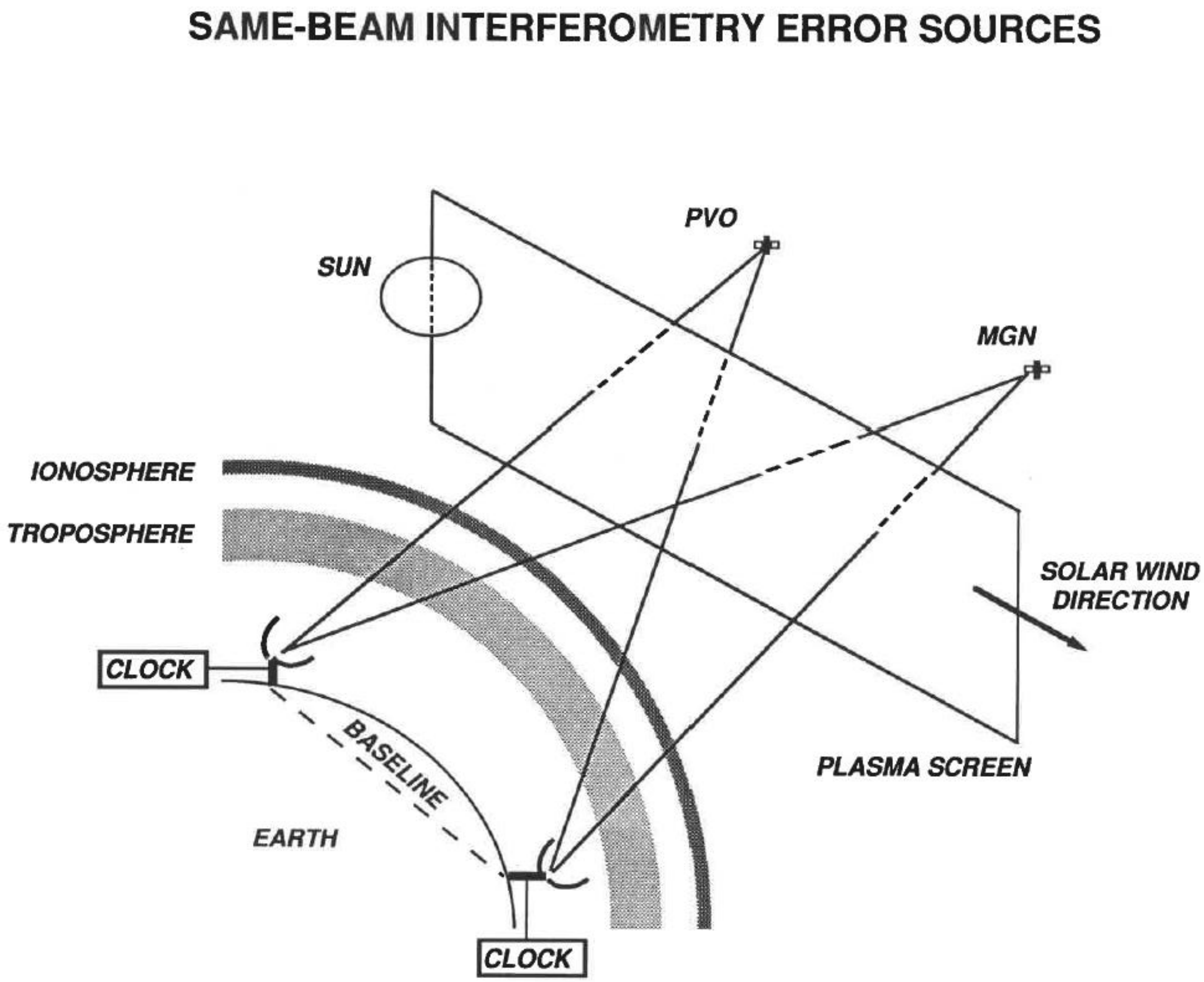




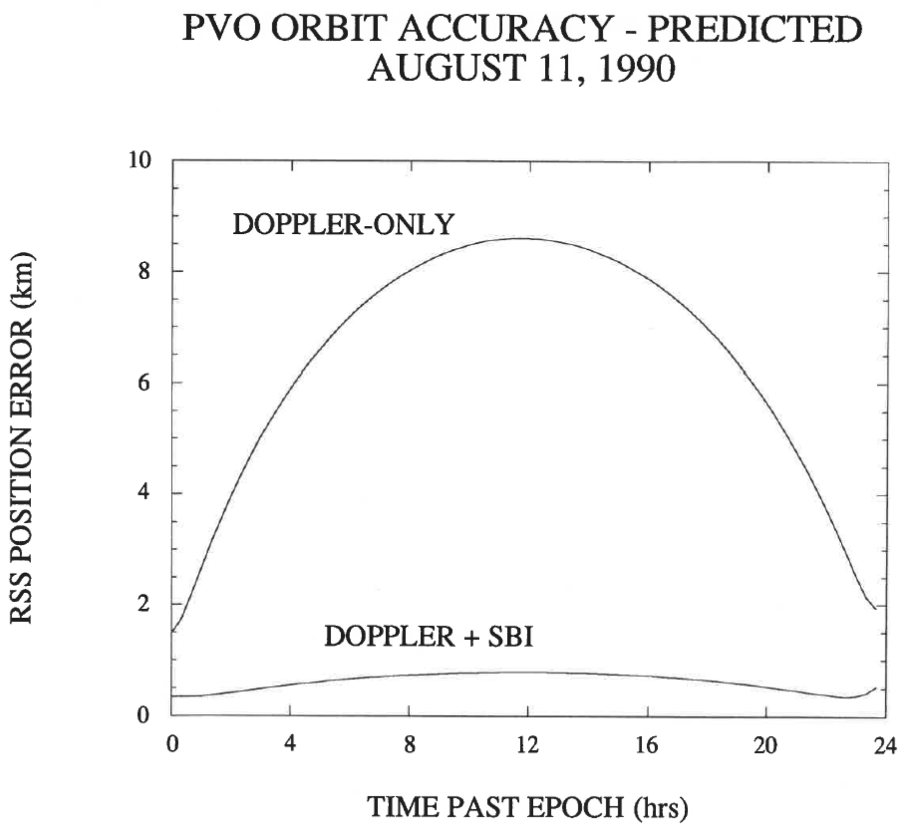
Simultaneous Delta-DOR: Same Beam Interferometry (1)

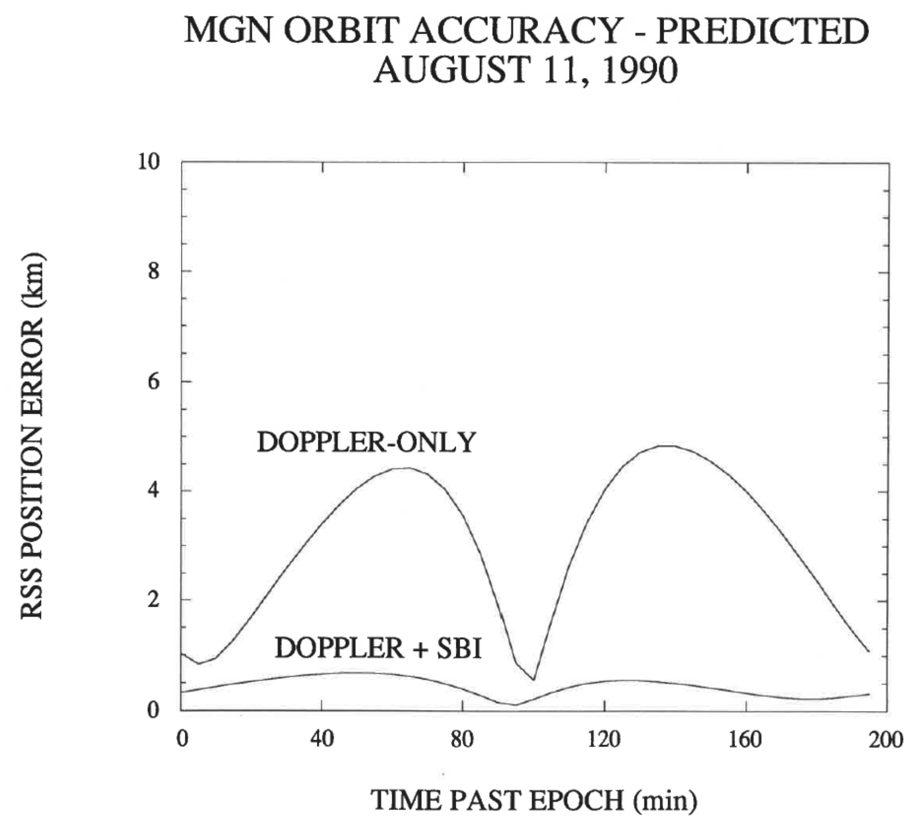
- Same Beam Interferometry (SBI) was proposed by Jim Border et. al. to support the tracking of the Magellan and the Pioneer Venus orbiters over 25 years ago [7]
- Like Delta-DOR, SBI uses double-differencing of signal arrival times to achieve highly accurate angular distance estimation
  - Eliminate clock biases, media delay, instrument delays, etc.
- Instead of using quasar as reference (5- 6 degree away), one can use a nearby spacecraft as a reference (less than a milli-degree)
  - Ground antennas do not need to point back-and-forth between the quasar and the spacecraft, thus increase observation time and simplify operation
  - Angular distance between spacecraft is much closer, thus increase accuracy from 10's nano-radian to nano-radians
- Quasar calibrations are needed only at the beginning and at the end of an overlapping pass

Simultaneous Delta-DOR: Same Beam Interferometry (2)



Simultaneous Delta-DOR: Same Beam Interferometry (3)





Simultaneous Delta-DOR: Same Beam Interferometry (4)

- SBI is more accurate, and operationally simpler than Delta-DOR
- Since the introduction of SBI, SBI was used or proposed for use in some deep space (including lunar) scenarios, e.g. approach/landing, ascent/docking, etc.

Examples:

- Q. Liu, F. Kikuchi, K. Matsumoto, et. al., "Error Analysis of Same-Beam Differential VLBI Technique using two SELENE satellites," Advances in Space Research 40 (2007).
- M. Chen, Q. Liu, "Study on Differential Phase Delay Closure of Same-Beam VLBI," 2nd International Conference on Computer Engineering and Technology, April 2010, Chengdu, China
- S. Chen, Q. Liu, "A Study on Accurate Same Beam Interferometry Differential Phase Delay Closure," 12th International Conference on Computer and Information Technology, October 2012, Chengdu, China
- T. Martin-Mur, D. Highsmith, "Mars Approach Navigation Using the VLBA," Proceedings of the 21st International Symposium on Space Flight Dynamics, Toulouse, France, September 28 – October 2, 2009

Can this Enable New Mission Concept and Science?

- An exercise of a solution looking for the right problems…
- This new “Multiple spacecraft per antenna” approach enables simultaneous communications, Doppler, ranging, and “delta-DOR” with different spacecraft, thus greatly reduces the burden of ground network. But can this approach also enable new mission concepts and science?
- Multiple spacecraft (CubeSats?) orbiting a moon or a planet to provide simultaneous Doppler measurements
  - Spacecraft life-time limitation, e.g. Class-D CubeSats, spacecraft at the harsh radiation environment of Jupiter
  - Short operation duration and graceful degradation
  - Spatial diversity of measurements to study system dynamics – gravity, atmosphere, and magnetic field
- Any ideas?

References

- [1] H. Price, J. Baker, F. Naderi, A Scenario for a Human Mission to Mars Orbit in the 2030s: Thoughts Toward an Executable Program – Fitting Together Puzzle Pieces & Building Blocks, Jet Propulsion Laboratory, California Institute of Technology. Presented at the Future In-Space Operations (FISO) Telecon, May, 2015.
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- [3] D. Bell, R. Cesarone, T. Ely, C. Edwards, S. Townes, “MarsNet: A Mars Orbiting Communications & Navigation Satellite Constellation,” IEEE Aerospace Conference 2000, March 2000, Big Sky, Montana.
- [4] K.Cheung, C. Lee, A Trilateration Scheme for Relative Positioning, IEEE Aerospace Conference 2017, Big Sky, Montana, March 2017.
- [5] K. Cheung, C. Lee, ”A Trilateration Scheme for GPS-Style Localization,” Interplanetary Network Progress Report, 42-209, May 15, 2017.
- [6] K. Cheung, D. Divsalar, S. Bryant, and C. Lee, “Simultaneous 2-Way Doppler and Ranging for Multiple Spacecraft at Mars,” IEEE Aerospace Conference 2018, Big Sky, Montana, March 2018.
- [7] J. Border, W. Folkner, R. Kahn, and K. Zukor, “Precise Tracking of the Megellan and Pioneer Venus Orbiters by Same-Beam Interferometry, Part I: Data Accuracy Analysis,” Interplanetary Network Progress Report, 42-110, August 15, 1992.
- [8] K.Cheung, C. Lee, “In-Situ Navigation and Timing Services for a Human Mars Landing Site Part 1: System Concept,” September 2017, 68th International Astronautical Congress, Adelaide, Australia.
- [9] D. Abraham, B. MacNeal, D. Heckman, Enabling Affordable Communications for the Burgeoning Deep Space CubeSat Fleet, SpaceOps 2016, May 2016, Daejeon, Korea.